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REVIEW

Producing more with less: reducing environmental impacts through an integrated soil-crop system management approach

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Abstract Balancing crop productivity with resource use efficiency and beneficial environmental consequences is essential for sustainable agricultural development worldwide. Various strategies and approaches have been proposed and debated, but turning the concept into management practices in the field with measurable outcomes over several scales remains a challenge. An innovative approach, Integrated Soil-Crop System Management (ISSM), for producing more grain with greater nutrient use efficiencies and less environmental pollution is presented. The ISSM approach has been used in China, in field experiments as well as in thousands of farmer fields, to substantially increase the yields of maize, rice and wheat while simultaneously increasing nitrogen use efficiency and reducing environmental footprints. The scientific principle, implementation strategy and procedures of ISSM are discussed and examples of its demonstrated successes at local and regional levels across China are given. Perspectives for further development of ISSM and expanding its potential impact are also proposed and discussed.

Keywords China, environmental protection, food security, high-yielding, nitrogen management

1 Challenge of current crop production in China

Despite the miracle of feeding 22% of the world population with 9% of the global arable land, China is facing unprecedented challenges in its agricultural sector. Demand for cereal grains is projected to increase by 50% by 2030, owing to both population growth and dietary changes[1]. However, the rates of yield increase have slowed[2], even stagnated in some areas, although the use of chemical fertilizers, one of the key drivers for decades-long yield improvement, continues to rise. For example, in the past 35 years cereal grain yields increased by only 65% in China, while chemical fertilizer use increased more than 2-fold. It is clear that continued increase in chemical fertilizer input alone is unlikely to meet the growing demand for food but will certainly aggravate the already-severe environmental problems.

Indeed, excessive nutrient use by China's agricultural systems has contributed to a number of serious environmental problems of considerable scale[3]. For example, emissions of anhydrous ammonia doubled and nitrogen oxides quadrupled between 1980 and 2000 based on 671 measurements[4,5]. Eutrophication is diminishing the aquatic life in major bodies of surface water, e.g., Lake Dianchi and Lake Taihu, and nutrients in agricultural runoff are the main culprits[6,7]. Furthermore, in major crop production regions of China, soil pH has decreased by 0.5 units from the 1980s to the 2000s, owing mainly to excessive use of N fertilizers[8]. Notably, the widespread water pollution and soil acidification are exerting additional constraints to agricultural productivity, given the general water shortage in many parts of the country and the multifaceted impacts of soil acidification on soil microbial activities, biogeochemical cycling of macro- and micronutrients, and rhizosphere processes[9,10].

Amid the environmental issues and relevant pressure to curb the pollution, Chinese agriculture also has to deal with land and labor competition in a context of climate change. There is a consensus among researchers, policymakers, and the general public that high input and high pollution is neither acceptable nor affordable in the long run. For China, to attain sustainable food security, it requires a fundamental shift in the way farming is routinely practiced. Here we present the Integrated Soil-Crop System

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Management (ISSM) approach, first introduced by Chen et al.[11] and Zhang et al.[1], as an innovative model for producing more grains with less input and less pollution. We review the scientific principle and implementation strategies of ISSM, summarize its demonstrated successes at field and regional scales and discuss ways to broaden its impacts in contributing to China's food security for the future.

2 Scientific principle and implementation strategy of ISSM

The initial publications on ISSM[1,11] reported experimental results showing considerable yield gains in maize while improving nutrient use efficiencies (NUE) and reducing environmental losses using the ISSM method. Subsequently, the same approach was employed to enhance the yields of wheat and rice, the other two major cereal crops, while addressing the nutrient issues[12]. The different cropping systems involve different growth conditions, requiring different management practices, but the scientific principles of the ISSM approach are the same and the implementation followed the same strategies.

Research addressing fertilizer use for crop production dates back several decades. The yield-goal approach in the USA, beginning with the seminal paper of Stanford[13], featured various soil, stalk and other tests (e.g., remote sensing technologies)[14–17]. Later, the optimum return method prevailed, which emphasizes the economically optimum N rate as defined through fertilizer trials[18]. More recent nutrient management approaches, e.g., the 4R program (right rate, right time, right placement and right Source) aim to maintain crop yields and grain quality while reducing N fertilizer input and lowering reactive N losses to the environment[19]. Wu and Ma[20] summarized a total of 75 reports worldwide with integrated nutrient management for sustaining crop yields and reducing environmental impacts. The progression in field research reflects our advancement in understanding the full-fledged effect of fertilizer use in crop production, from the initial wonder of yield-enhancement to its limitation (yield plateau and thus the economic optimum N rate) and to the sometimes devastating side-effect of water pollution.

In China, considerable research has been devoted to testing the high-yielding potential of crops without nutrient constraints. For example, maize yields of >15 Mg·ha^{-1} have been reported in more than 195 fields over the past two decades[21]. Such yields are nearly three-times the average yield of 5.9 Mg·ha^{-1} in 2014[2]. However, the exceptionally high yields were achieved by agronomists under the most favorable ecological conditions combined with high nutrient inputs without regard for the economic costs and environmental risks[21]. For example, N application rates in 43 high-yielding maize studies averaged 747 kg·ha^{-1}, with some sites exceeding 1000 kg·ha^{-1} N (e.g., 1170 kg·ha^{-1} at Laizhou site in 2005)[11]. These application rates were more than double the amount of N required to attain the high yields (about 300 kg·ha^{-1}). While testing the yield potential might be the main purpose of such studies, in reality this type of research might have misled farmers and practitioners into believing that high fertilizer inputs were needed to achieve higher grain yields[22].

Scientists at China Agricultural University, in collaboration with partners from more than 30 institutions, developed the ISSM approach based on over 30 years of research findings and collective field experiences[11]. The scientific principle of ISSM is to maximize the use of resources from aboveground (solar radiation and temperature) and below ground (nutrients in the root zone), and synchronize N supplies from soils, environment and in-season applications with the dynamic requirement of the growing crop[11]. The implementation strategies consist of two components. First, maximal use of solar radiation and periods with favorable temperatures are achieved by selecting appropriate crop cultivars, sowing dates and planting densities for the growing conditions at a given site. Second, the most effective N fertilization scheme is designed to ensure adequate N supply while minimizing potential N losses based on an in-season root-zone N management technique. For the latter, total N supply in the root zone, including residual soil nitrate-N and applied chemical N fertilizer, is managed so as to match the amount of N required for the high-yielding crop in amount, space and time.

Temperature and thermal conditions are important for regulating crop growth[23], affecting the emergence, flowering and maturity dates of crops[24]. Low efficiency in exploiting temperature and thermal resources during the growing season often leads to low grain yield and large yield gaps[25]. For a given region, the thermal conditions cannot be changed, but it is relatively straightforward to design an optimal cropping system with the crop cultivar, sowing date and planting density to make maximum use of solar radiation and periods with favorable temperatures based on long-term weather data[26]. For example, using the Hybrid-Maize simulation model[27] and 15-year weather data near Beijing, a high-yielding maize production system was designed with simulated yields ranging from 11.6 to 16.9 Mg·ha^{-1} (depending on the weather in different years), compared to an average of 8.9 Mg·ha^{-1} in prevailing practices[11]. The gap between model simulation and farmer yields indicates potential yield improvement by optimizing cropping parameters (e.g., cultivar, sowing date and plant density) to best utilize particular thermal conditions.

Nutrient uptake by plant roots takes place in the rhizosphere, which is the important interface where interactions among plants, soils and microorganisms occur. Rhizosphere processes can also be the bottleneck limiting the transformation, availability and flow of nutrients from soil to plants[10]. Plant roots not only regulate plant morphological traits to adapt to soil environmental conditions but also modify rhizosphere processes through their physiologic activities, such as proton release, redox changes, in particular exudates of organic acids, phosphatases and some signaling substances[28,29]. The root/rhizosphere management strategies in ISSM emphasize maximizing the efficiency of root and rhizosphere processes in nutrient mobilization, acquisition and use by crops rather than depending solely on chemical fertilizers in intensive farming systems[1].

In ISSM, understanding the dynamics of N demand and dry matter accumulation by high-yielding crops is key in order to synchronize N supply with the demand[11]. Research has shown that the amount of N required per unit grain yield decreases as the crop yield increases, indicating that N physiologic efficiency (calculated as the ratio of grain yield with N uptake) improves with high-yielding system[30–32]. Unfortunately, most farmers still believe that more fertilizer and higher grain yield are synonymous[33].

Another important fact is that crop dry matter as well as N and P accumulation in the mid to late growing season, e.g., the post-anthesis stage for maize, the post-elongation stage for wheat or the heading stage for rice, significantly influence grain yield[34–36]. This observation differs from some earlier studies that N accumulation in major cereal crops occurs primarily in the pre-anthesis stage, and that grain yields are largely dependent on the translocation of pre-anthesis assimilates and N uptake[37,38]. In ISSM, the proportion of N applied during the growth period is calculated according to the N demand curve of the crop, with two applications for wheat (before planting and around stem elongation stage), three for maize (before planting, and at 6- and 10-leaf stages), and three for rice (before planting, and at tillering and heading stages). In practice, farmers often apply most of the N fertilizer before sowing or during early growth[39].

Based on improved understanding of the relationship between crop, soil and nutrients, the strategies for implementing the ISSM approach include: (1) optimizing nutrient inputs and taking all sources of nutrients into consideration; (2) dynamically matching soil nutrient supply with crop requirement spatially and temporally; (3) effectively reducing N losses in intensively managed Chinese cropping systems; and (4) taking all yield-enhancement measures into consideration[1].

For a given site, the most appropriate cropping strategies (e.g., planting date, crop maturity, and seeding density) are designed based on crop model simulations for optimal use of solar and thermal resources. And, supply module for the formulation of nutrient and water rate based on soil tests and the needs of the growing crops. Pest management and soil tillage are optimized according to local ecological conditions in ISSM approach.

3 Demonstrated success of ISSM at field and regional scales

When the ISSM approach was used in one experiment with maize in North China, grain yield increased from 6.8 Mg·ha^{-1} under farmer practice to 13 Mg·ha^{-1} without increasing N fertilizer input. Meanwhile, N use efficiency (calculated as yield per unit fertilizer N applied, kg·kg^{-1}) increased from 26 to 57 kg·kg^{-1} (see details in Chen et al.[11]). In other on-farm studies (n = 18), the same approach increased maize yield (14.8 Mg·ha^{-1}) by 70%, compared to farmer practice, with only 38% more N fertilizer input, and the N_2O emission and greenhouse gas (GHG) intensities (expressed as kg of N_2O or carbon dioxide equivalents per Mg of yield) of the ISSM system were reduced by 12% and 19%, respectively[40].

From 2009 to 2012, a total of 153 site-year field experiments were conducted to test the utility of ISSM in 11 provinces covering the main agroecological zones for rice and wheat. Unlike maize, it is more challenging to increase grain yields while reducing the environmental cost for rice and wheat as tiller crops because they change in population structure within the growing seasons. As for maize, the ISSM approach was used to design the whole production systems for rice and wheat according to local climate and soil-water conditions, drawing upon appropriate crop cultivars, sowing dates, densities and advanced nutrient management. Consequently, the ISSM approach increased yields by 21%–87% compared to farmer practice without substantially increasing N fertilizer inputs. Nitrogen use efficiency increased by 24%–32%; total reactive N losses and GHG emission density decreased respectively by 50%–56% and 31%–47% compared to farmer practice (Table 1)[12].

Further testing of the ISSM approach in a total of 22 provinces at 5147 site-years produced encouraging results. On average, N fertilizer inputs decreased by 24%, yields increased by 12%, NUE increased by 40%, while net farming income went up by about 132 USD·ha^{-1}[41]. The demonstrated success involving both experimental plots and farmer fields provides sound evidence that ISSM is an effective approach for increasing crop productivity and NUE, which represents an important case for sustainable intensification of agriculture.

Support policies and effective measures are essential to enable smallholder farmers to adopt the ISSM approach. In response to the demonstrated success of ISSM, the Ministry of Agriculture and Rural Affairs of the People's Republic of China sponsored a series of national programs for scientists to collaborate across different disciplines and to conduct on-farm demonstrations in a wide range of soil and crop systems. From 2005 to 2010, the Ministry of Agriculture and Rural Affairs of the People's Republic of China funded a national Soil-Testing and Fertilizer Recommendation Program to optimize fertilizer management covering all agricultural counties with nearly 6 billion

Table 1 Comparison of grain yield, N rate, N use efficiency (PFP_N), reactive N (Nr) losses, greenhouse gas (GHG) emissions and their intensity between Integrated Soil-Crop System Management (ISSM) and farmer practice (FP). Nr losses and GHG emissions were estimated by models with these emissions expressed as kg of N or CO_2 per equivalents ha and their intensity as kg of N or CO_2 equivalents per Mg of grain yield. Data from Chen et al.[12]

Crop	Treatment	Yield/($Mg \cdot ha^{-1}$)	N rate/($kg \cdot ha^{-1}$)	PFP_N/ ($kg \cdot kg^{-1}$)	Nr losses/ ($kg \cdot ha^{-1}$ N)	Nr intensity/ ($kg \cdot Mg^{-1}$ N)	GHG/(kg CO_2 per ha eq)	GHG intensity/(kg CO_2 per Mg eq)
Rice	ISSM	8.5	162	54	55	4	9535	1077
	FP	7	209	41	66	10	10343	1574
	Difference/%	21	–22	32	–16	–56	–8	–32
Wheat	ISSM	8.9	220	41	59	6	4182	463
	FP	5.7	210	33	65	12	3707	671
	Difference/%	56	5	24	–9	–50	13	–31
Maize	ISSM	14.2	256	56	125	9	4575	329
	FP	7.6	220	43	120	17	4436	621
	Difference/%	87	16	30	4	–50	3	–47

CNY (~923 million USD). This national action included soil testing, formulation of fertilizer products for site/crop-specific conditions, production and provision of the formulated fertilizers to farmers. About two-thirds of Chinese farmers benefited from the initiative with yield increasing by 10% and NUE improved from 30% to 38%[42].

Recognizing the urgency of producing more with less environmental damage, the Ministry of Agriculture and Rural Affairs of the People's Republic of China announced the Zero Increase Action Plan in 2015 for national fertilizer use[42]. The plan stipulates that annual increase in total N fertilizer use nationwide will be controlled to less than 1% from 2015 to 2019, with zero increase starting in 2020. This plan was strongly supported by the outcome of ISSM, proving that it is possible to produce more grains with greater efficiency of fertilizer use and lower environmental costs. The Ministry of Agriculture and Rural Affairs of the People's Republic of China will also initiate extension programs with total funding of 5 billion CNY (~800 million USD) to support the implementation of the Zero Increase Action Plan in different regions across China over the next 5 years.

4 Strategies for further development and scale-up

First, the ISSM approach relies on integrated management of cropping parameters (e.g., cultivar, sowing time and seeding density) with soil conditions and nutrient supplies (e.g., tillage, fertilization and irrigation) to optimize the use of natural and applied resources. The methodology adapted for ISSM with dynamic cropping parameters should be region- or site-specific and must be tailored to local conditions, as there is no simple solution to the complex problems of smallholder farmers in diverse agricultural systems. Implementing ISSM practices requires knowledge of what is required by plants for the optimum level of production, in which form, at what time and how these requirements can be integrated to obtain the highest productivity levels within acceptable economic and environmental limits[20]. The impact is different for different region in China and determining this impact will require continuously site-specific research. The benefits of ISSM are achievable provided there are (1) investments in agronomic research that incorporates an ecosystem perspective, (2) efforts to pursue this across disciplinary and institutional boundaries, and (3) technologies, arrangements and incentives that make it viable for farmers to adapt and adopt more knowledge-intensive forms of agriculture. Thus, the success with multiple goals will require continued and expanded efforts nationwide to integrate plant breeding, agronomy, soil science, plant nutrition and plant protection. More adaptation measures (e.g., drought-tolerant varieties) should be contained in the ISSM system to tackle climate change in the future.

Second, recycling of organic resources (animal and human wastes and green manure) has been essential in maintaining soil quality and sustaining food production in China[43], although the adoption of current ISSM for cereal crop production often ignores animal manure application, mainly because of labor shortage. China's organic resources amount to 3900 Tg in dry matter annually[44]; animal manure alone is estimated to contain 15 Tg of N and 10 Tg of P in 2009[45]. Proper management of organic nutrients would reduce N and P chemical fertilizers by about 4.5–7.5 and 10 Tg annually, assuming fertilizer equivalence of 30%–50% for manure N and 100% for manure P, respectively. Additional improvements in recycling of the organic materials can occur when the benefits of C sequestration are coupled with increases in crop yields from adoption of cultivation practices that reduce yield losses from abiotic and biotic stresses, such as returning straw back to the soil, increasing applications of organic manures and using reduced tillage[46].

Most arable land in China has low indigenous soil fertility[43]. It is quite challenging to achieve high crop yields in such soils, which often also have relatively low capacities to retain N and P and are therefore prone to nutrient losses. In future, a key aspect of ISSM is the importance of building up the soil organic carbon pool in Chinese croplands by appropriate, sustainable management strategies, such as returning large quantities of crop resides to the soil and/or decreasing losses of soil organic carbon through erosion, mineralization, and leaching. Adopting and sustaining the use of such practices is necessary to restore soil quality and achieve the higher crop yields needed to meet China's food security challenges.

Third, transferring knowledge and extending the field adoption of ISSM approach to the vast majority of smallholder farmers in China requires more investment and support from public and private sectors. The current difficulty in implementing ISSM resides in the lack of effective channels to transfer the technologies to millions of Chinese farmers[47]. Smallholder farming with high variability between fields and a poor infrastructure has restrained the efficiency of ISSM practices in China, where the average land per farm is 0.6 ha and individually managed fields are generally 0.1–0.3 ha[11]. Additionally, because of the low profits in the agricultural sector, an increasing number of educated young people have left the farming community for city jobs, leaving farming tasks to the older and less-educated individuals. Therefore, how to engage these *left-behind* farmers, to train and motivate them to adopt science-based management technologies, such as ISSM, remains a major challenge.

Wide adoption of the ISSM approach across the country will rely heavily on effective and multichannel agricultural technology transfer and extension, engaging both public and private sectors. This may be achieved through a combination of multiple pathways: (1) government-supported programs with vastly improved national agricultural extension systems[47]; (2) enterprise-sponsored initiatives embodying incorporation of relevant scientific results into commercial products, which would require close collaboration between the research community and business entities such as fertilizer companies; and (3) agricultural scientists working directly with and transferring knowledge to farmers through the Science and Technology Backyard (STB) model[48,49]. The STB is an innovative extension-education model, which involves faculty and students from agricultural universities living in the villages among farmers, transferring knowledge, advancing participatory innovation and the adoption of ISSM-based technologies, meanwhile engaging public and private enterprises for improved services. The model was first proved successful in Quzhou County, with a 5-year average yield improvement from 68% of the attainable level to 97% by 71 lead farmers, and from 63% to 79% county-wide, along with increased resource and economic benefits. A total of 71 STBs are now operating in China, covering a variety of cropping systems. Further expansion of the STB model will help broaden the implementation of ISSM-based management technologies for food security in China.

Globally, environmental and economic constraints (e.g., rising cost of fossil fuels) dictate that future food supplies must be attained through enhancing production efficiency rather than further increasing fertilizer inputs, especially N and P[50,51]. Producing more grains with fewer resources and environmental costs is attainable, as evidenced in China using the ISSM approach. Such an approach may also provide valuable information for sustainable agricultural development in other nations, particularly in rapidly developing countries such as Brazil, India, and Mexico. Like China, these countries achieved substantial yield increases from green-revolution technologies during the 1960s–1980s, but rates of yield gains have slowed markedly in the past 10–20 years[2], even though agricultural inputs such as nitrogen and phosphorus have continued to increase. We believe that the ISSM principle and approach are applicable elsewhere. It should be possible to meet the growing food demand with more sustainable intensive agriculture on existing cropland, thereby sustaining other natural resources by avoiding the conversion of forest, grassland and marginal lands to agriculture and supporting other ecosystem services, such as wetland preservation, wildlife conservation and carbon sequestration.

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